

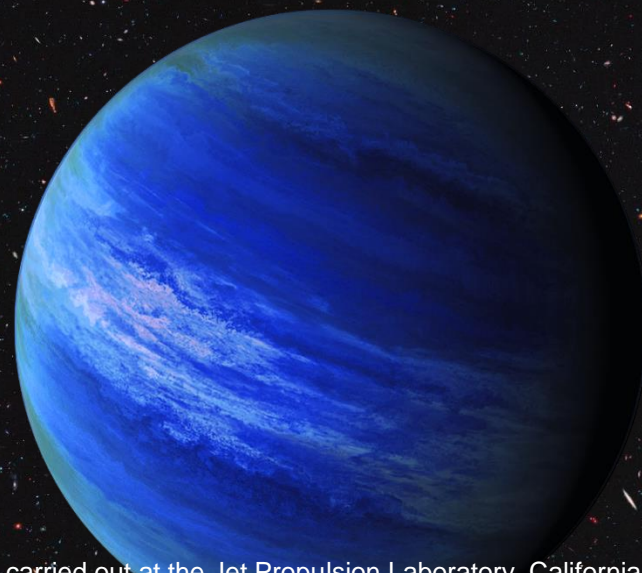
Imaging Exoplanets with the WFIRST Coronagraph Instrument

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Manager, WFIRST Coronagraph Instrument

Jet Propulsion Laboratory

California Institute of Technology

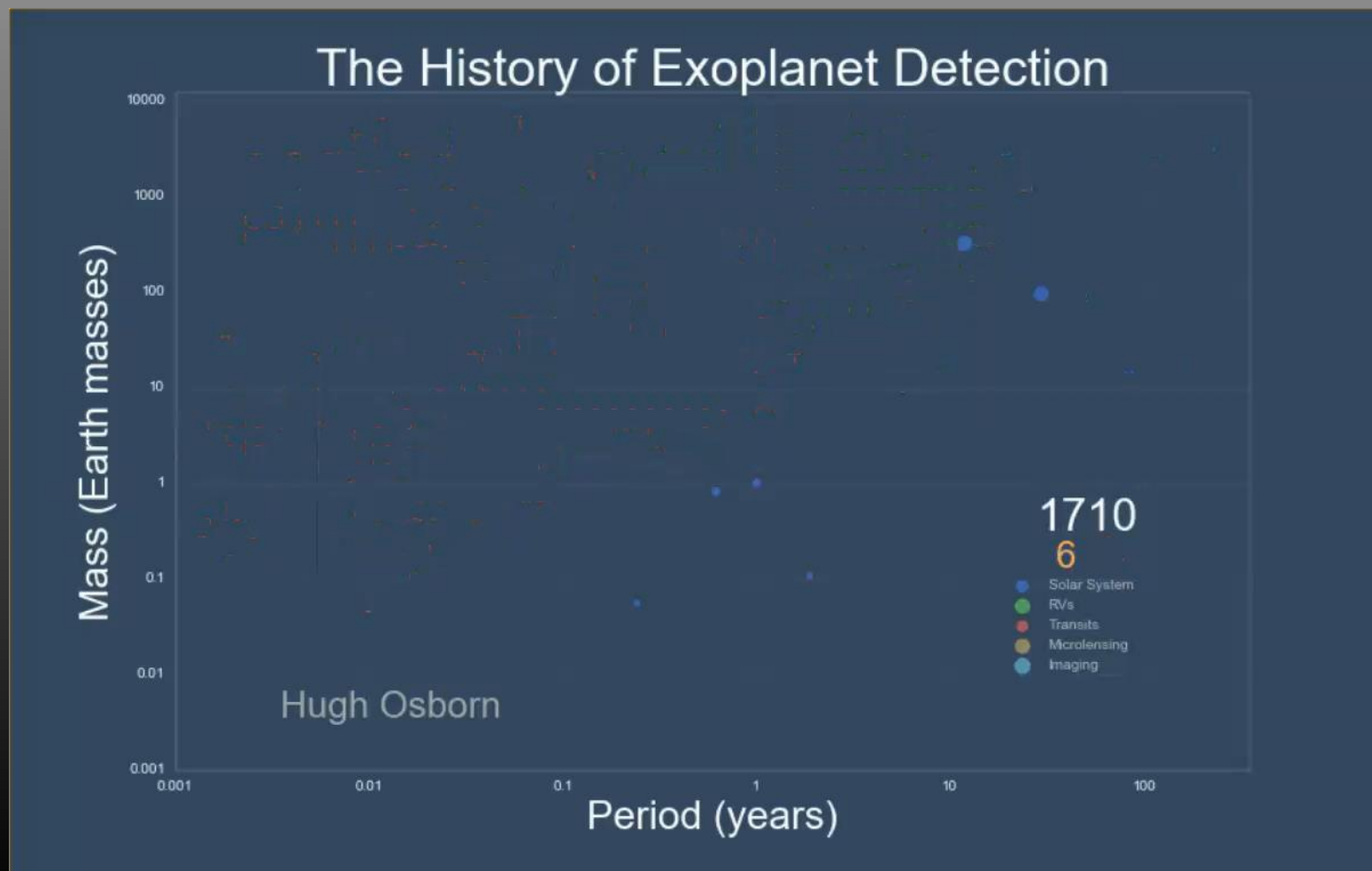


© 2018 California Institute of Technology. Government sponsorship acknowledged. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The decision to implement the WFIRST mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.



Exoplanets – A major shift in understanding the Universe

Mass vs Orbital Period

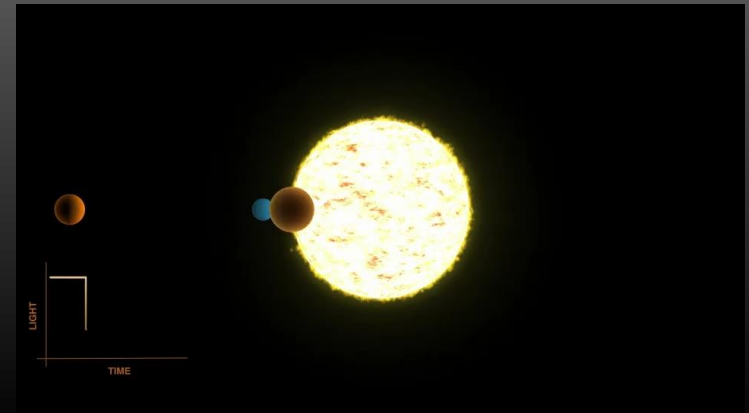


How do we find Exoplanets?

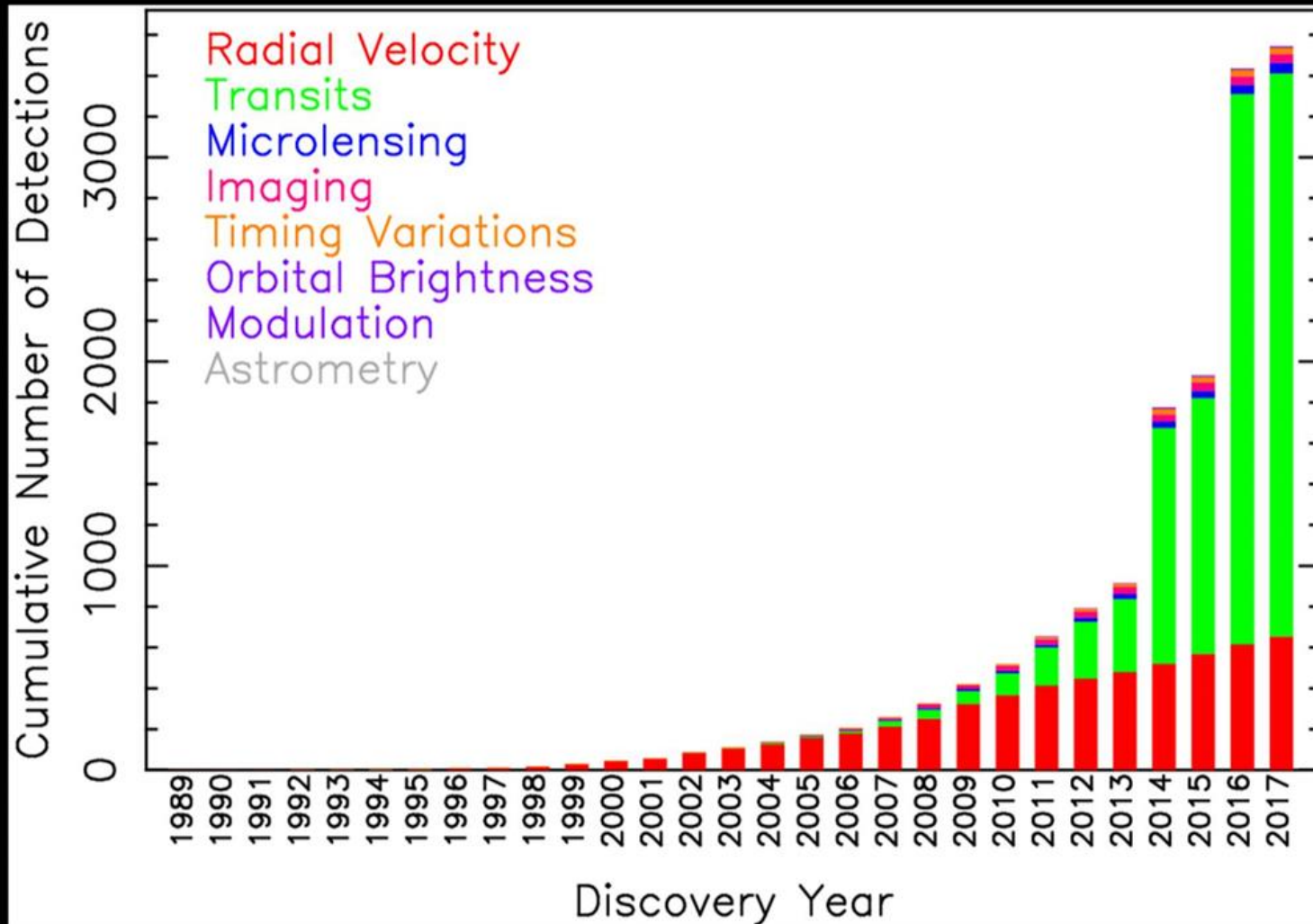


- Doppler Spectroscopy (Radial Velocity)

- Exoplanet transits



Number of Exoplanets discovered doubles every 2 years



Exoplanet Missions

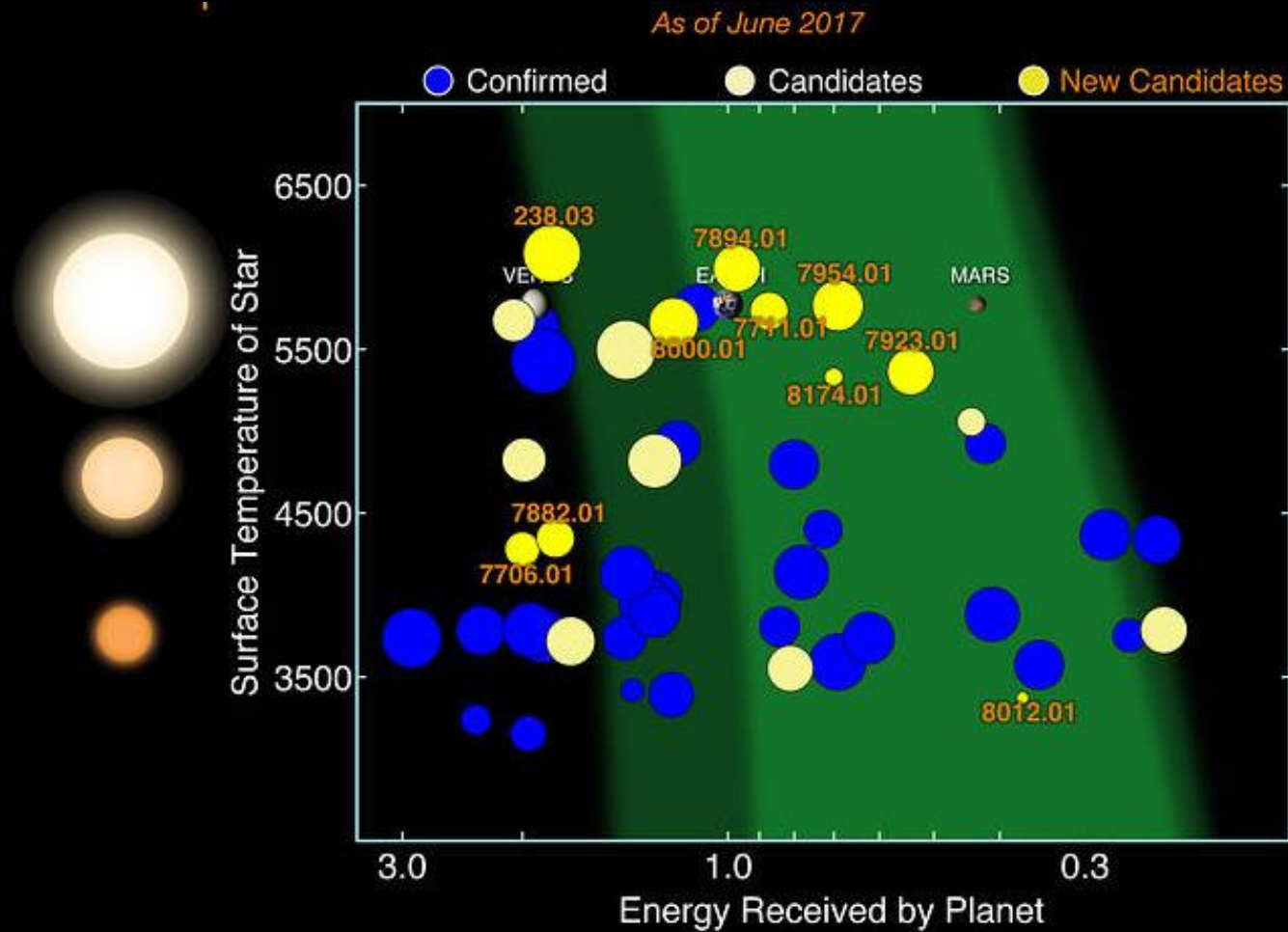


Ground Telescopes with NASA participation

⁵ 2020 Decadal Survey Studies

- ¹ NASA/ESA Partnership
- ² NASA/ESA/CSA Partnership
- ³ CNES/ESA
- ⁴ ESA/Swiss Space Office

Kepler Habitable Zone Planets

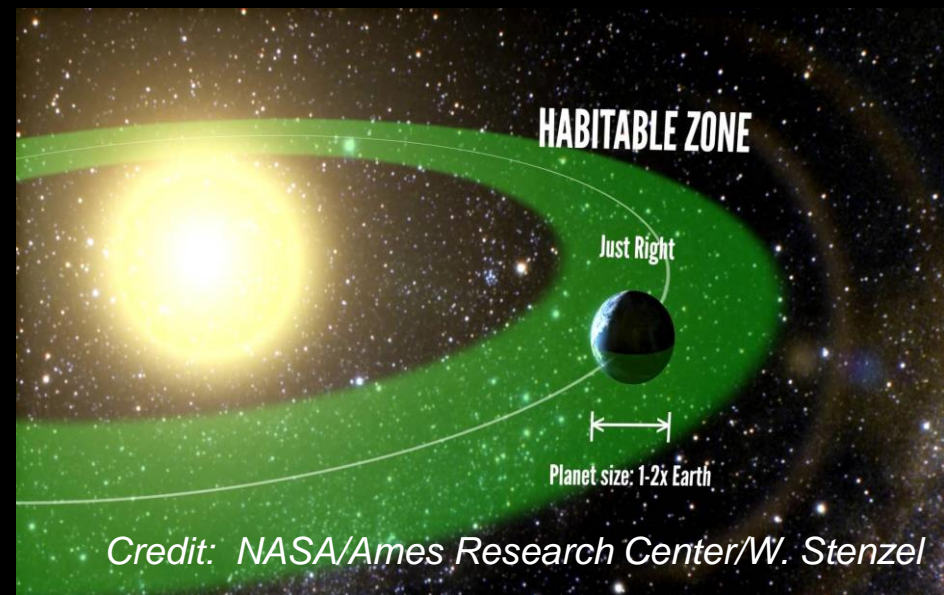
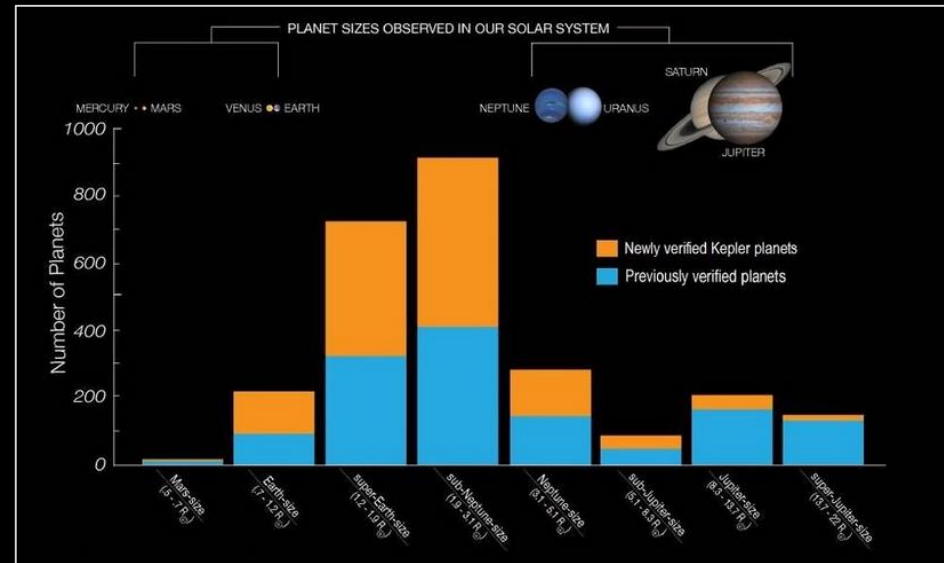


Recent Data Release 25 identifies additional HZ candidates and their reliability,
S. Thompson et al.

Credit: NASA/Ames Research Center/W. Stenzel

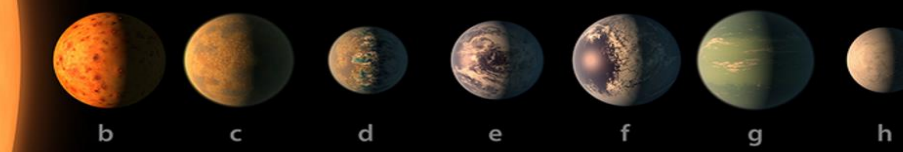
Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky
2. Small planets are the most common type in the Galaxy
3. Earth-sized planets (0.5 to ~1.5 Earth radii) in the Habitable Zone are common



Exoplanet Science News

Courtesy: E. Mamajek

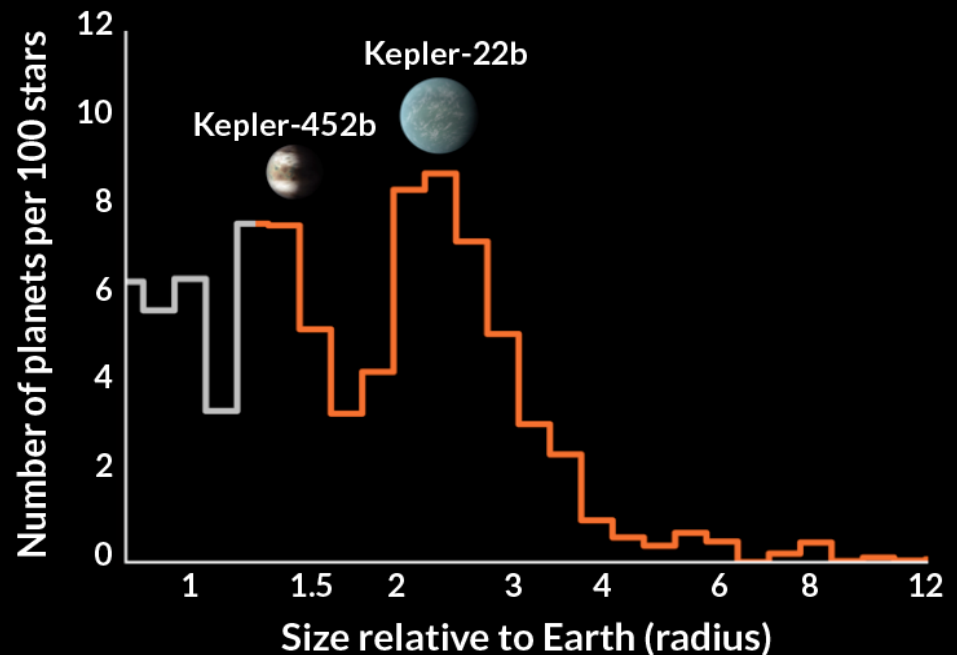


- Gillon et al. (2017, Nature) reported discovery w/Spitzer that the nearby ultra cool dwarf TRAPPIST-1 has 7 transiting Earth-sized exoplanets.

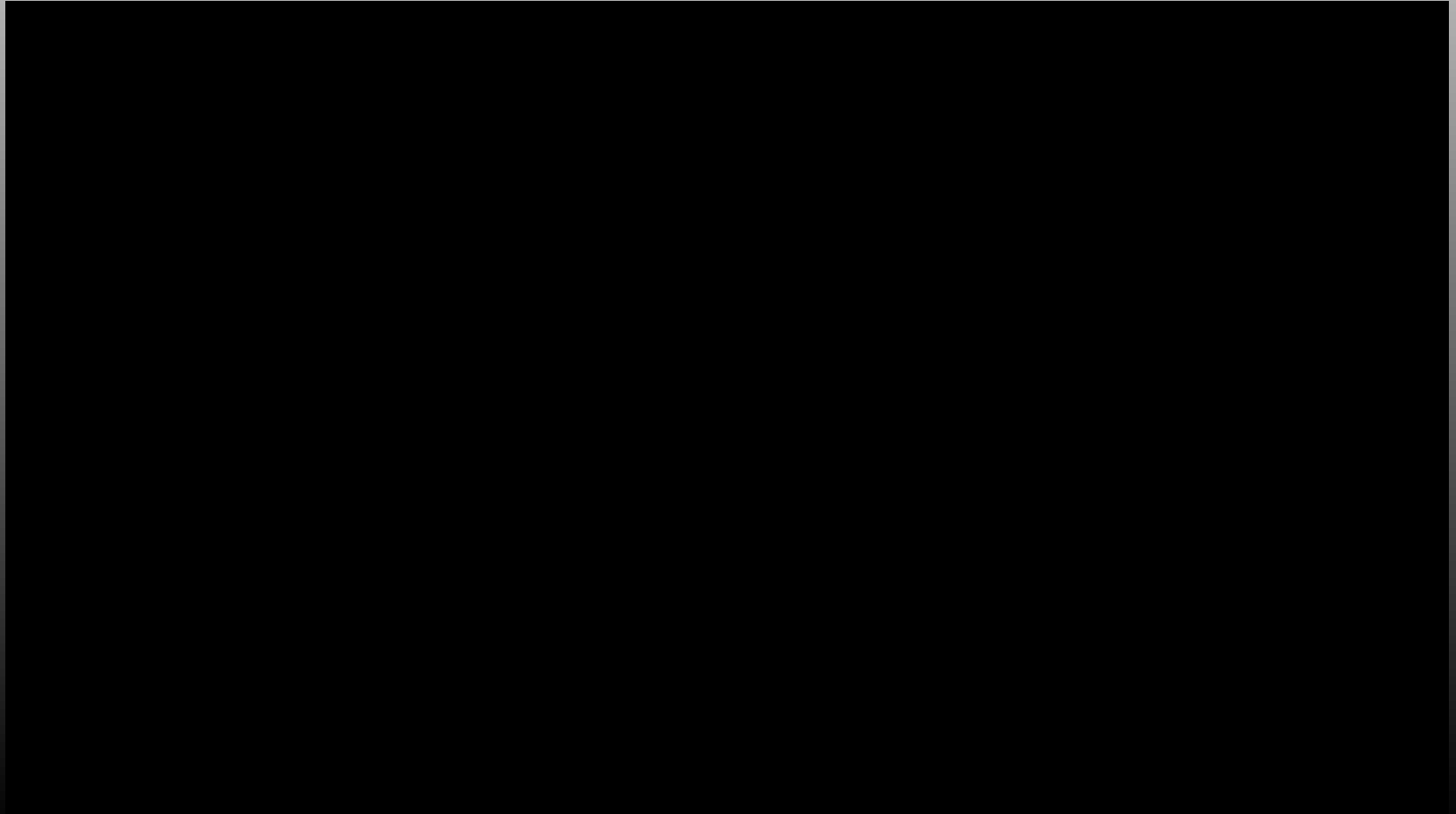


- Feng et al. 2017 found evidence for four planets in new HARPS data of the nearby star τ Ceti.

- Fulton et al. (2017) reported strong evidence for gap between “super-Earth” and “sub-Neptune” exoplanets using Kepler data + spectroscopic data for stars from Keck.



Direct Imaging with a Coronagraph



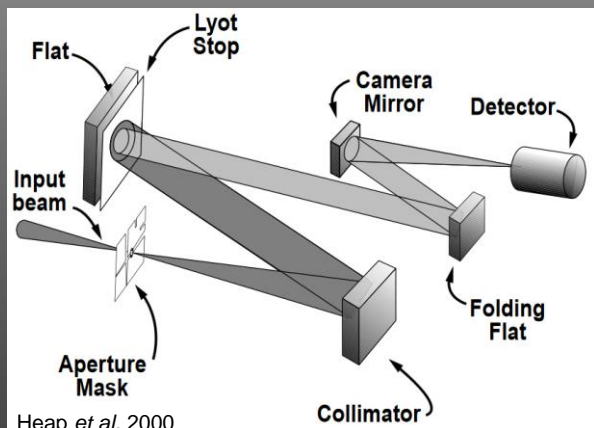
Imaging exoplanets with previous coronagraphs in space – no active optics

Hubble has had three Lyot coronagraphs used in its instruments to look at planets:

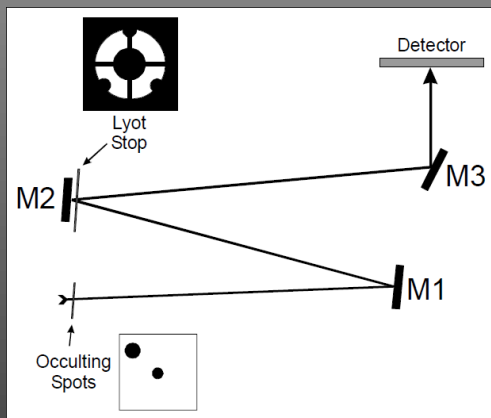
STIS

ACS/HRC

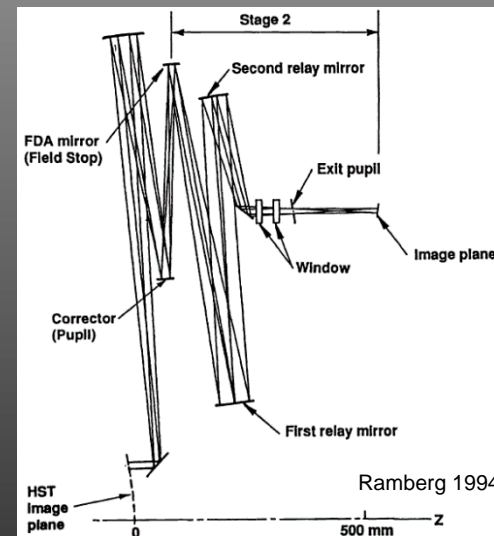
NICMOS



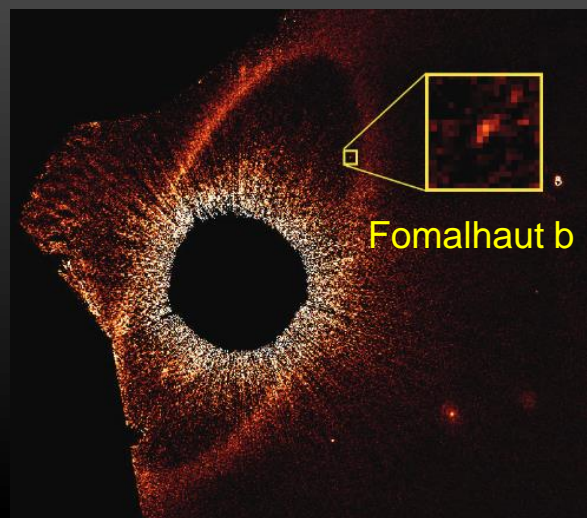
Heap et al. 2000



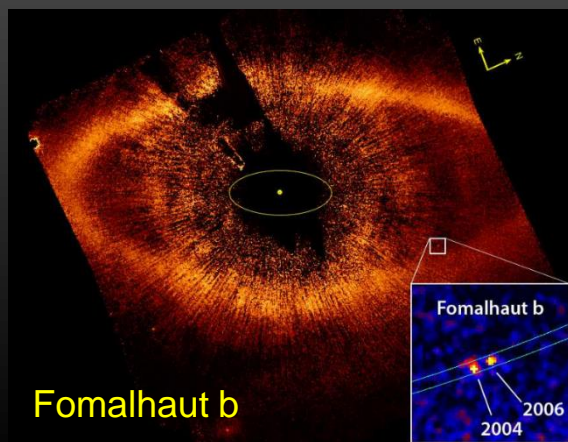
Krist et al. 2003



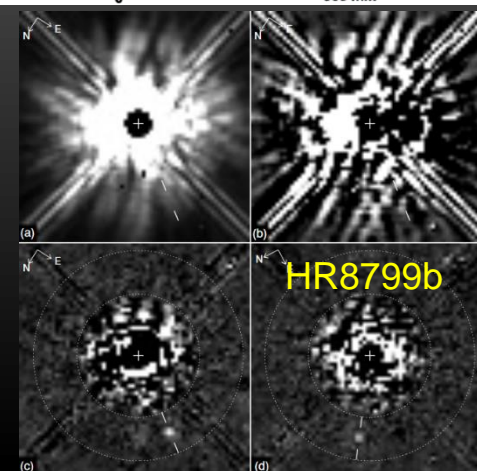
Ramberg 1994



Fomalhaut b



Fomalhaut b



HR8799b

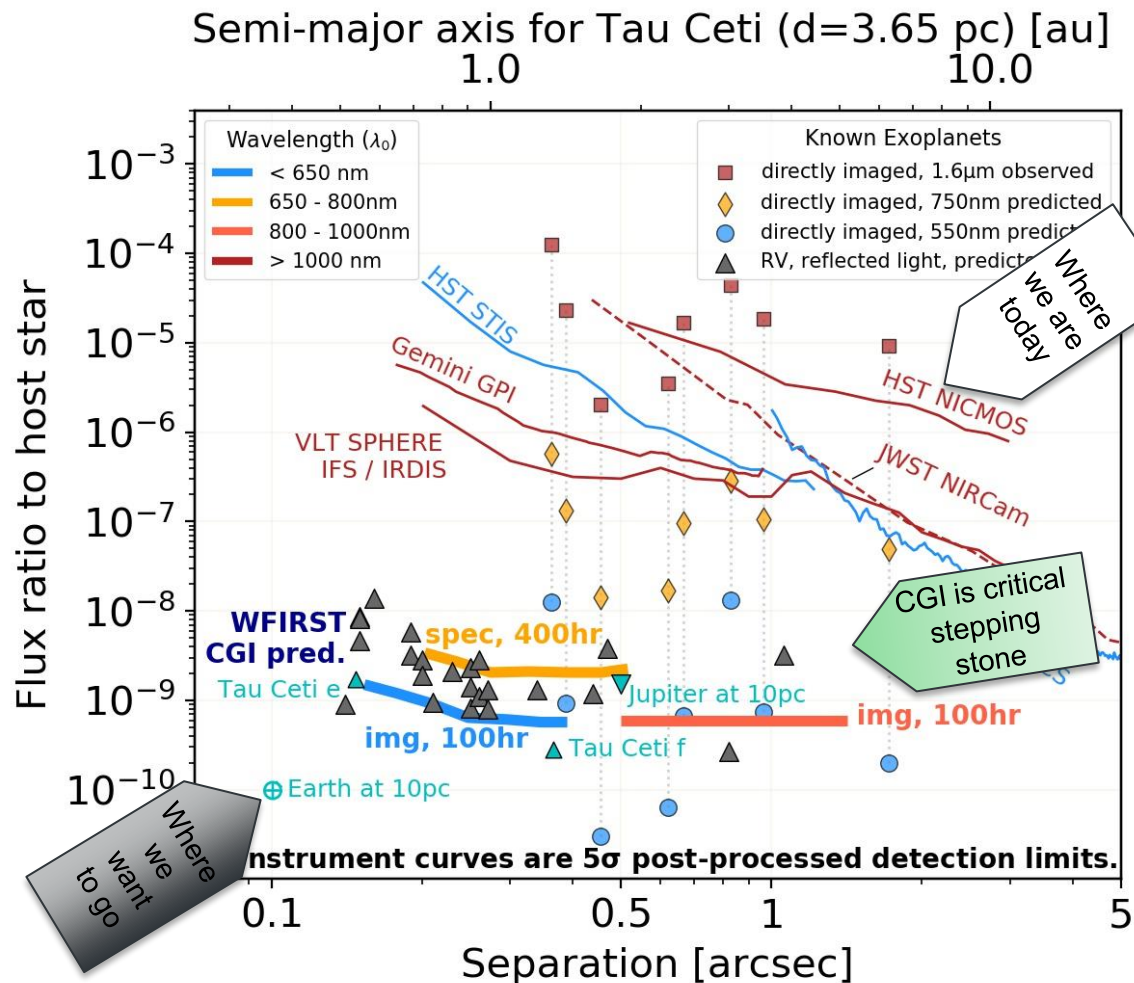
Coronagraph Instrument is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets

CGI projected performance is a 1000 fold improvement in contrast compared to space- and ground-based state-of-the-art observatories

- Enabled by active control of optical wavefront errors and pointing

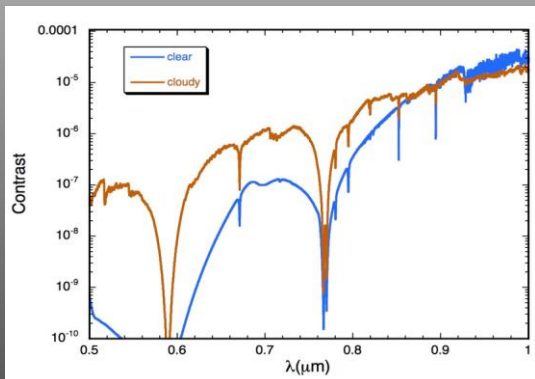
Optical spectra of exoEarths at 10 pc requires a further x10 improvement in contrast and x2 in spatial resolution

CGI is a major stepping stone that will obtain optical spectra of mature exoJupiters

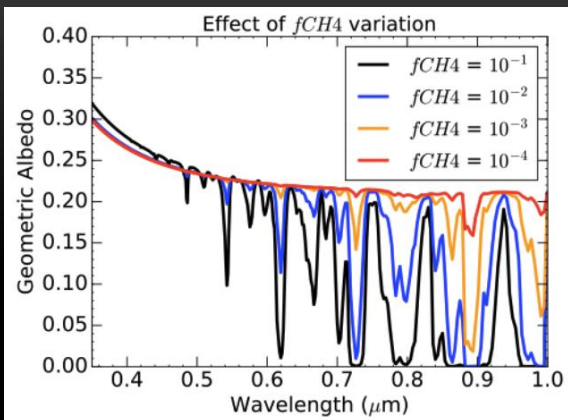


CGI Exoplanetary Science Themes

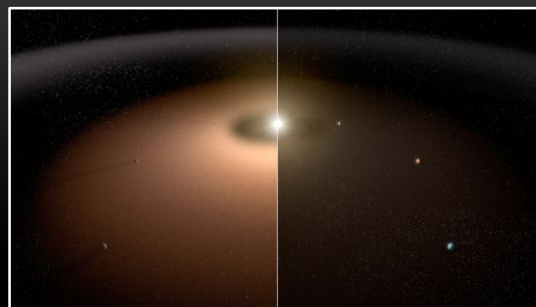
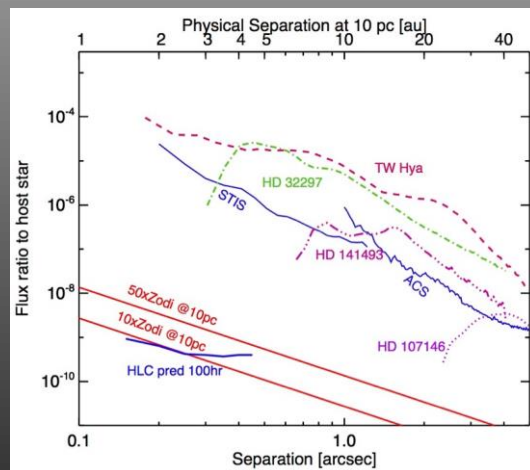
Self-luminous, young super Jupiters: atm. properties



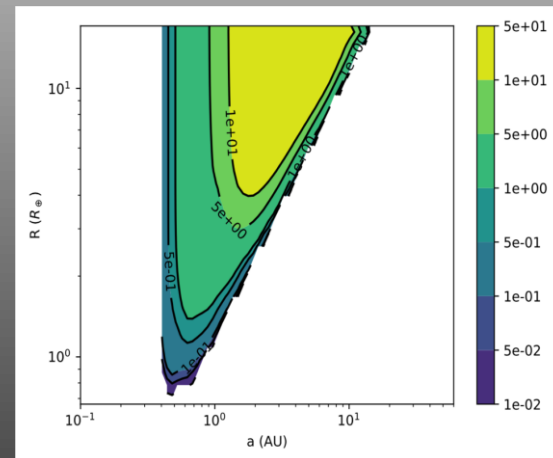
Mature Jupiter analogues in reflected light: mass & atm. properties



Circumstellar disks: Protoplanetary (young) Debris (mature) Exozodi (mature, HZ)



Possible blind searches for giant planets



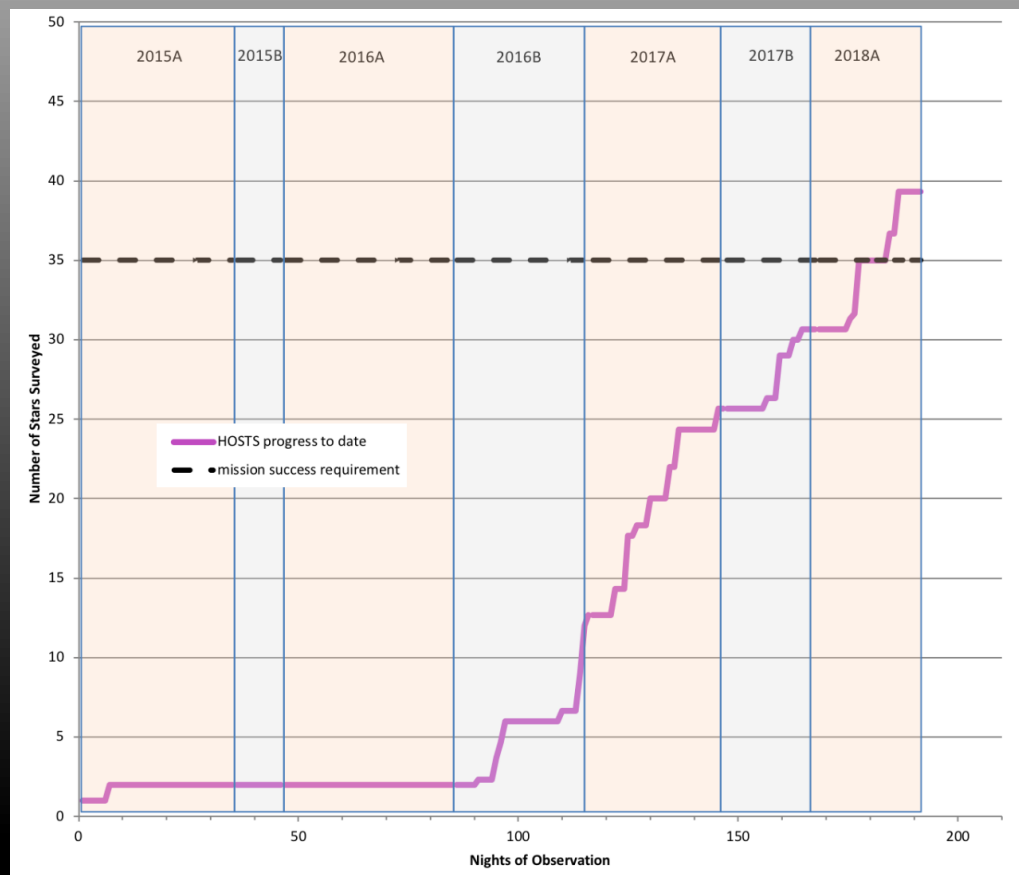
Possible characterization of Habitable Zone of nearby systems



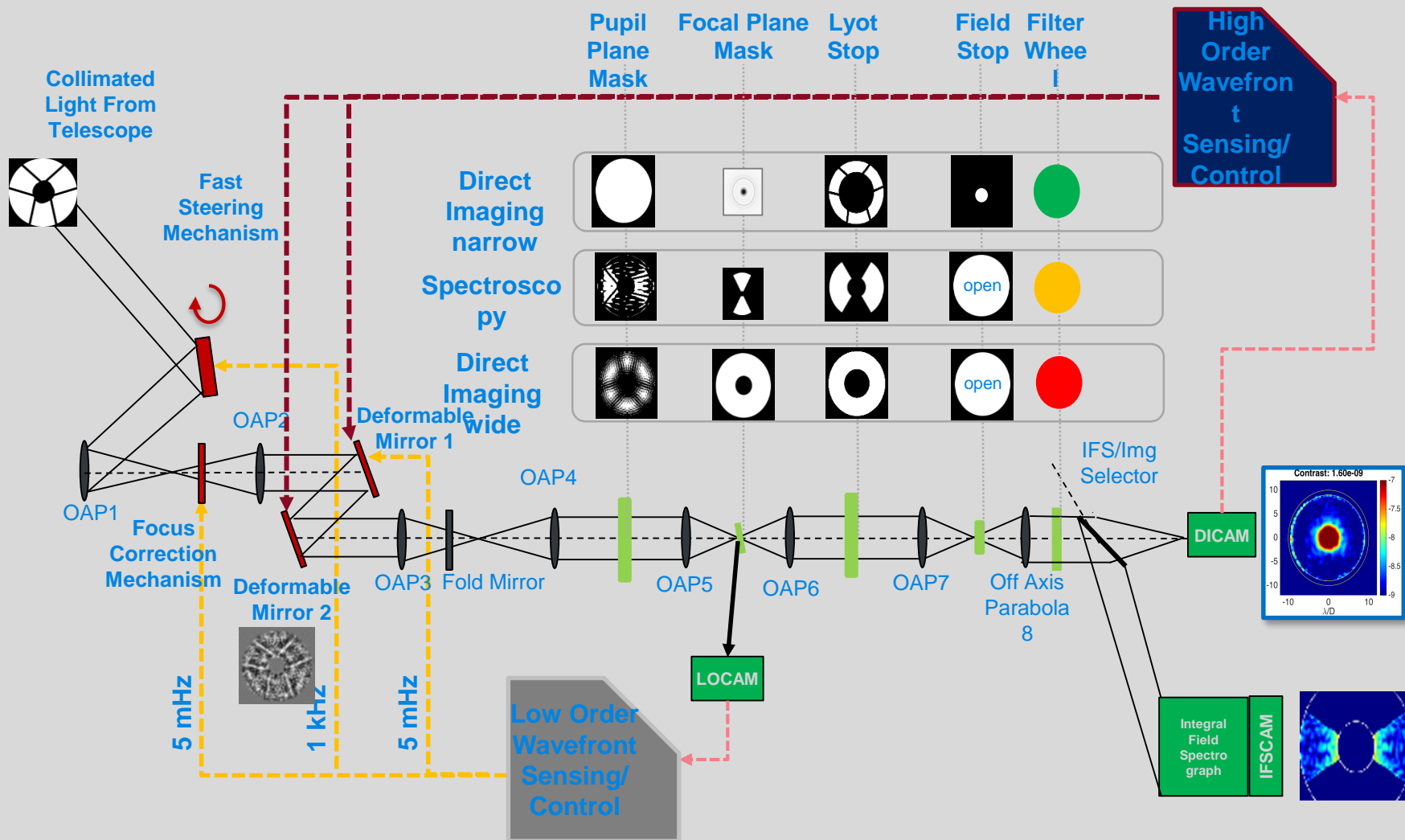
Dust around stars

- Large Binocular Telescope Interferometer result – most nearby sunlike stars are not very dusty

Large Binocular Telescope Interferometer Stars Surveyed



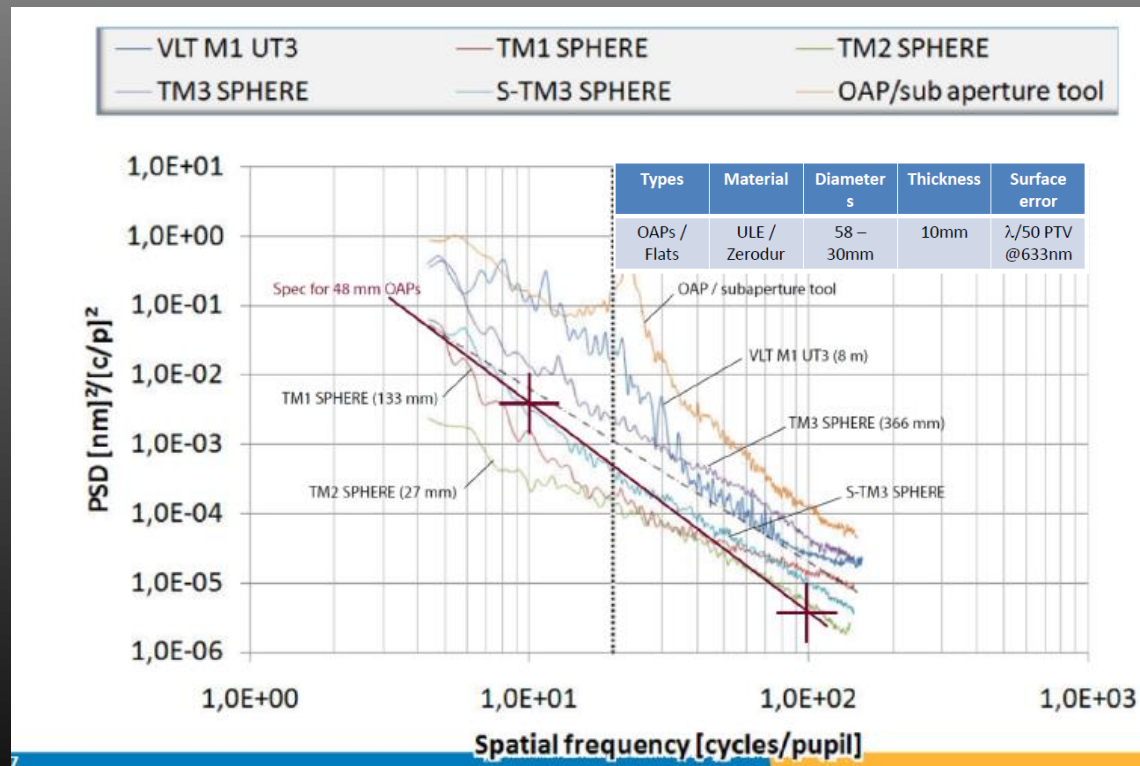
WFIRST CGI – Actively Controlled Optical Imaging Instrument With Coronagraph Masks



Optics following the Deformable Mirror are Critical



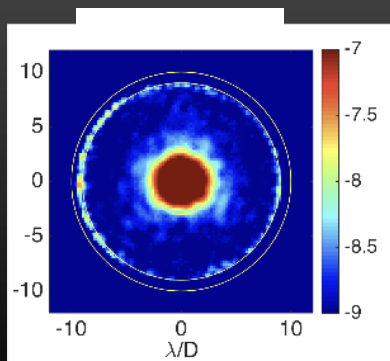
- High precision off-axis parabolas to be provided by LAM using stress polishing techniques
- Critical since post deformable mirror; need to maintain wavefront error accuracy



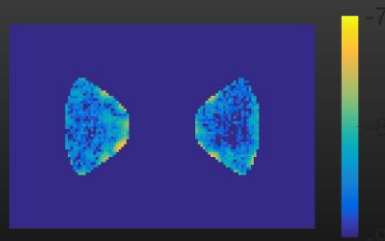
➤ Three Required Technology Demonstration Modes:

Name	λ_{center} (nm)	Spectral Band-width	Channel	Mask Type	Working Angle	Starlight Suppression Region	Can use w/ linear polarizers?
Imaging w/ Narrow FoV	575	10%	Imager	Hybrid Lyot	3-9 λ/D	360°	Y
Spectroscopy	760	18%	Spectrograph	Shaped Pupil	3-9 λ/D	130°	N
Imaging w/ Wide FoV	825	10%	Imager	Shaped Pupil	6.5-20 λ/D	360°	Y

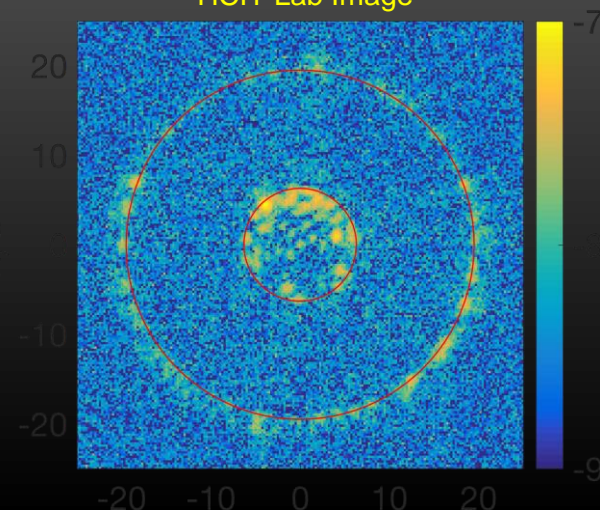
Imaging w/ Narrow FoV
HCIT Lab Image



Spectroscopy
HCIT Lab Image

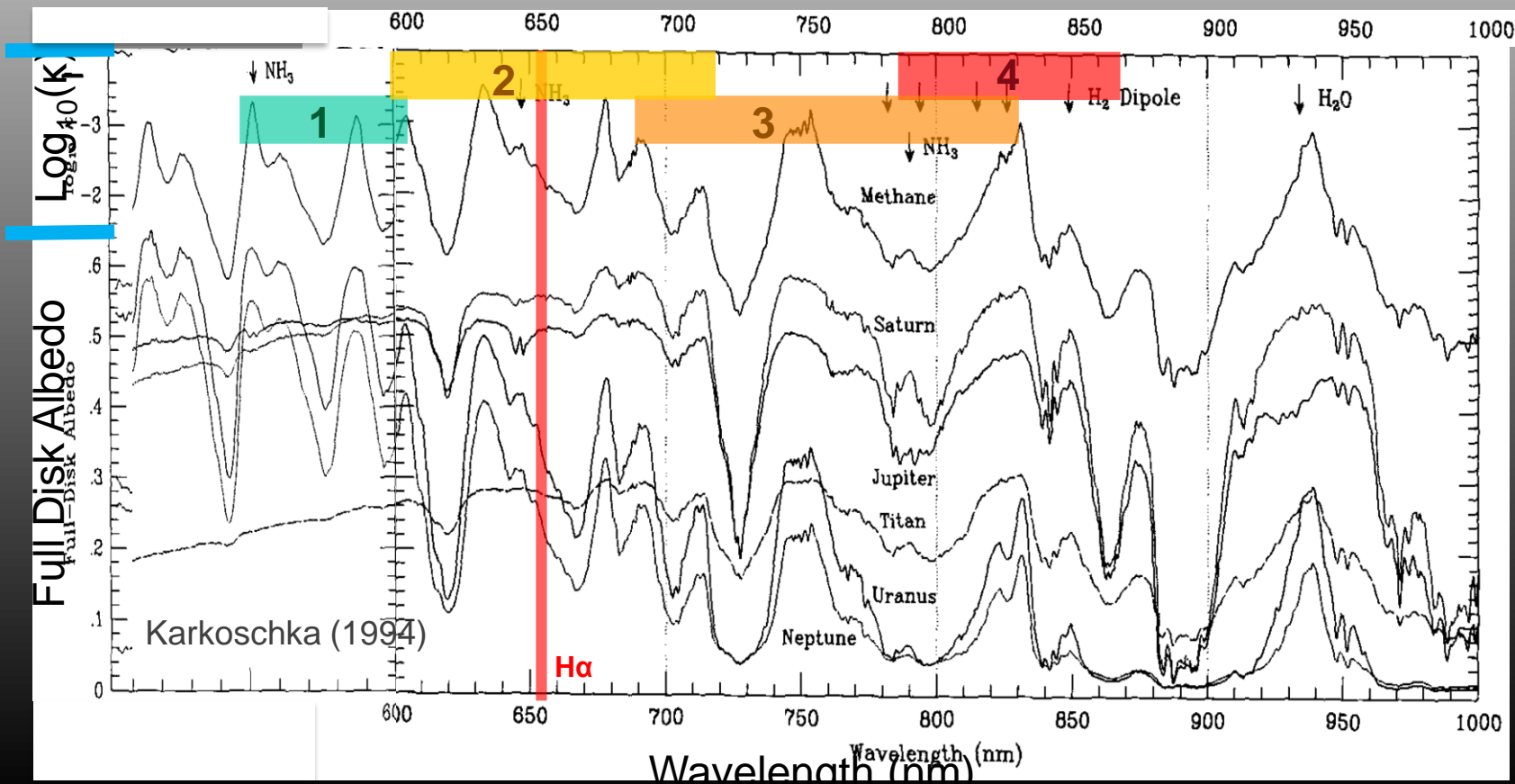


Imaging w/ Wide FoV
HCIT Lab Image

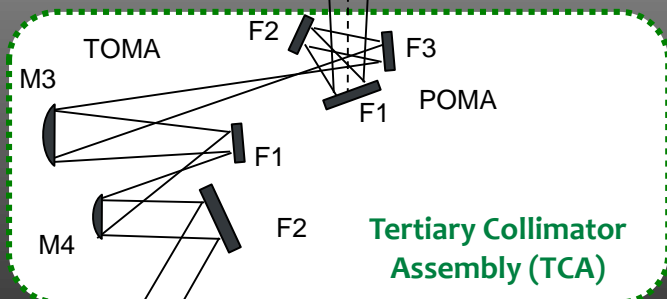
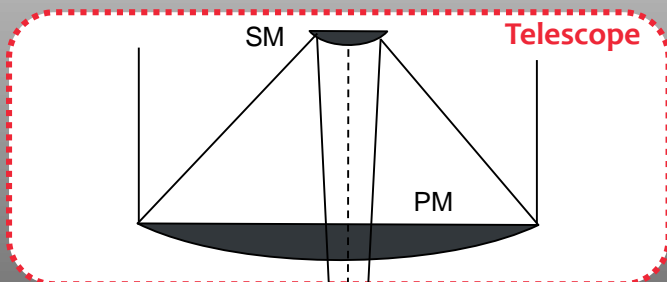


Coronagraph Instrument Filters

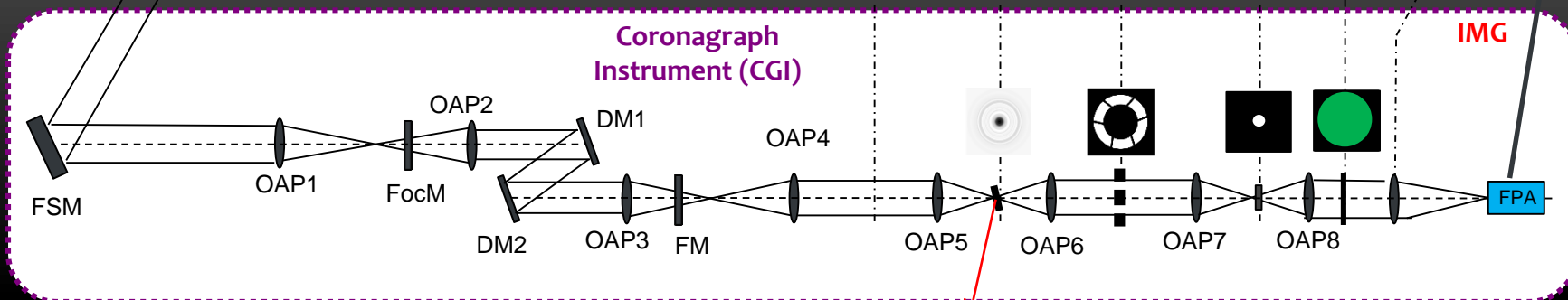
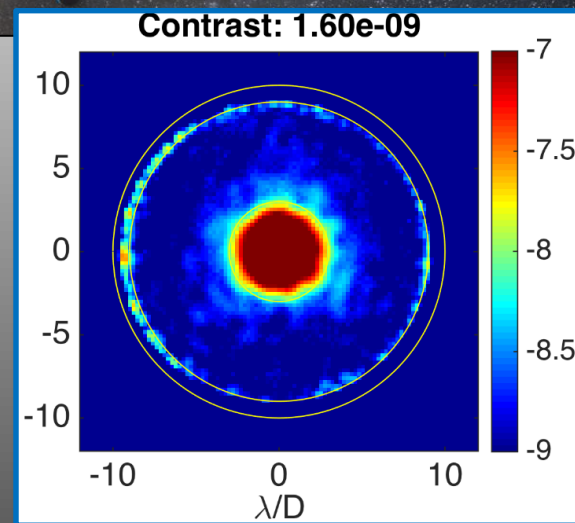
Span 550-850 nm



Imaging with Narrow Field of View Mode



Dark hole for planet photometry and discovery centered at 575 nm with annular FOV from 3-9 λ/D



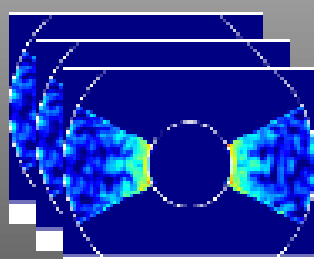
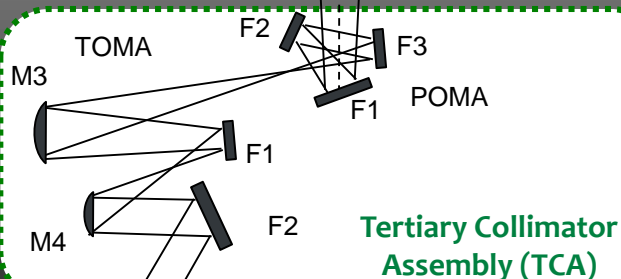
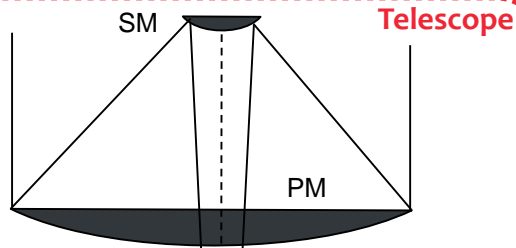
to LOWFS

IMG

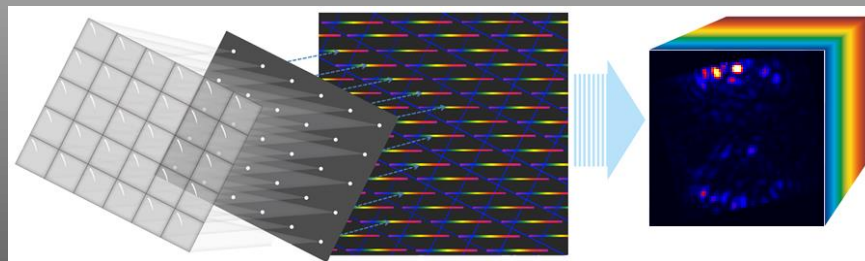
FPA

Spectroscopy Mode with Integral Field Spectrograph (IFS)

The IFS uses 3 18% bands to produce $R=50$ spectra from 600 to 970nm



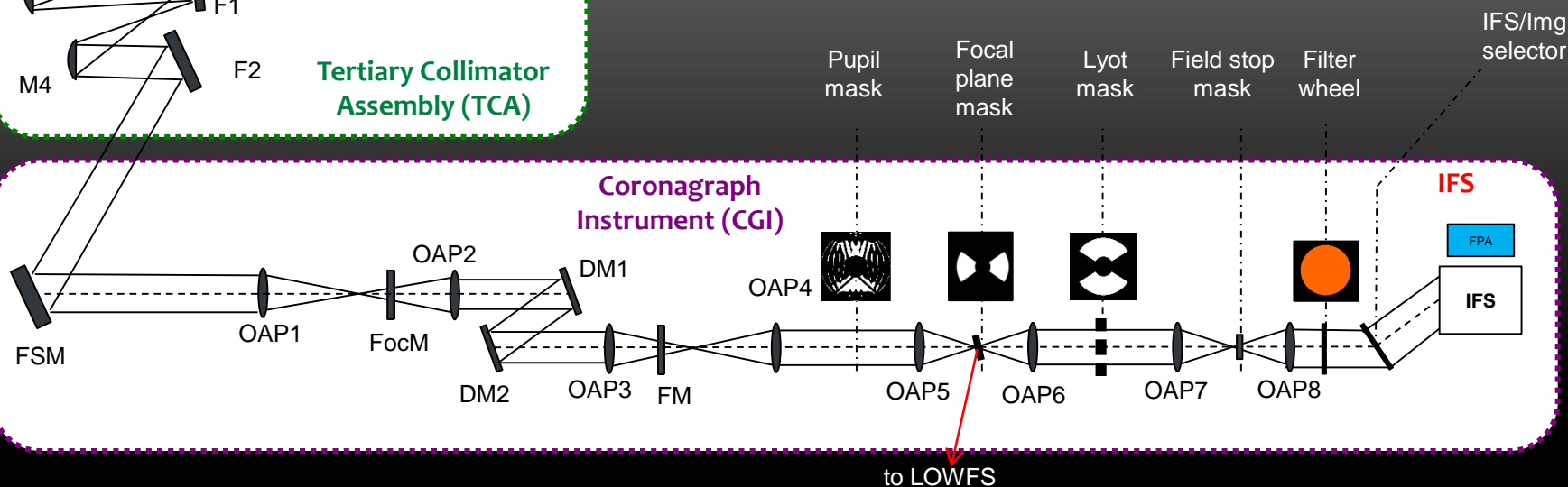
SPC images in 3 18% bands



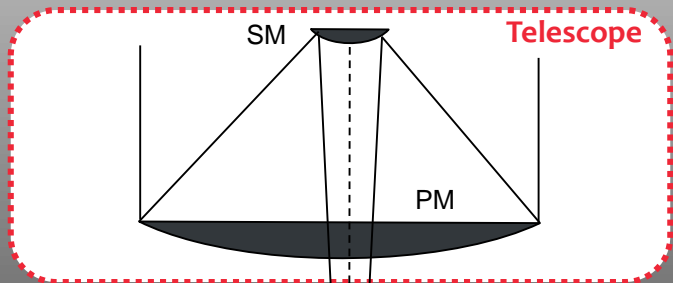
lenslet array

pinhole mask

dispersed lenslet images



Imaging with Wide Field of View Mode



Disk imaging at wavelengths 508 and 721 nm, with outer working angle of $20 \lambda/D$

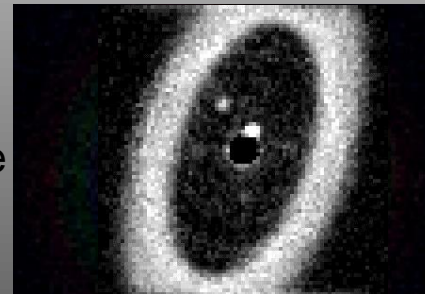
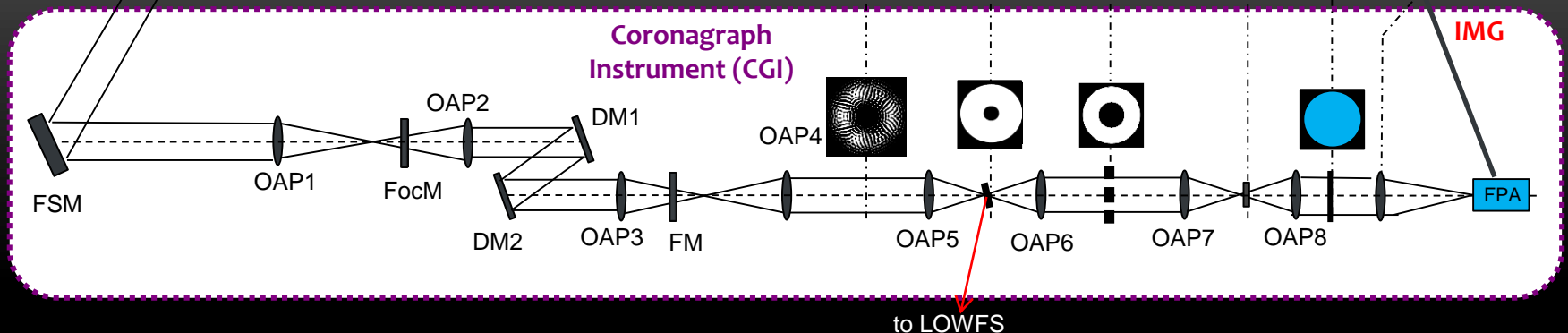
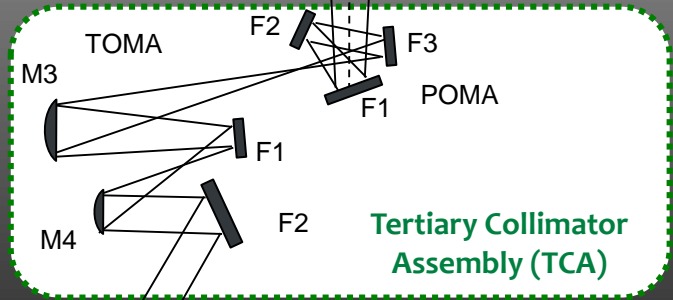


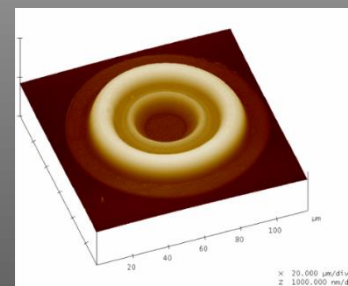
Image from 2015 Exo-C STDT Final Report



Successful Technology Maturation for Coronagraph Instrument

- Pupil plane and focal plane masks for starlight suppression
 - Hybrid Lyot Coronagraph (HLC)
 - Shaped Pupil Coronagraph (SPC)
- Photon-counting electron-multiplying (EM) CCD for detection of very faint planets
 - Teledyne e2v
 - 1Kx1K pixels
 - Radiation characterization
- Deformable mirrors for telescope surface error and drift correction
 - Northrop Grumman Xinetics
 - 48x48 actuators
 - Electrostrictive PMN (lead magnesium niobate)
 - Still requires environmental test of interconnect
- Coronagraph system-level performance demonstrated using a testbed with flight-like observatory disturbances:
 - Optical telescope simulator, with simulated pointing and thermal drift errors
 - High-order wavefront sensing and control to system to measure/correct telescope errors
 - Low-order wavefront sensing and control system to measure/correct telescope drift and provide tip/tilt error signal

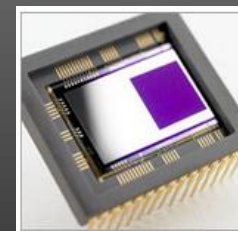
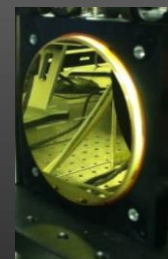
HLC mask image with an atomic force microscope



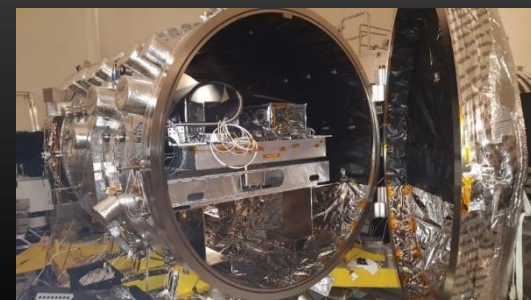
SPC mask image with an atomic force microscope



Xinetics 48 x 48 DM used in JPL's HCIT



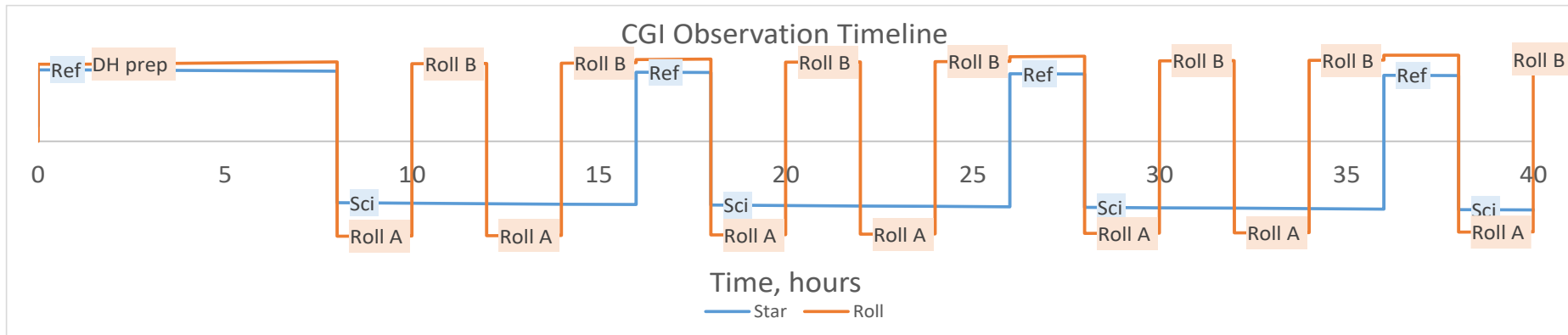
E2V EMCCD used in photon-counting mode



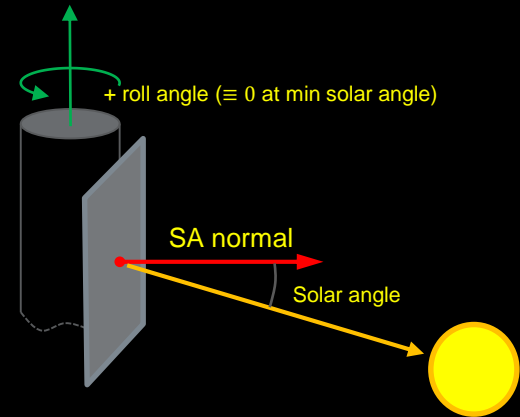
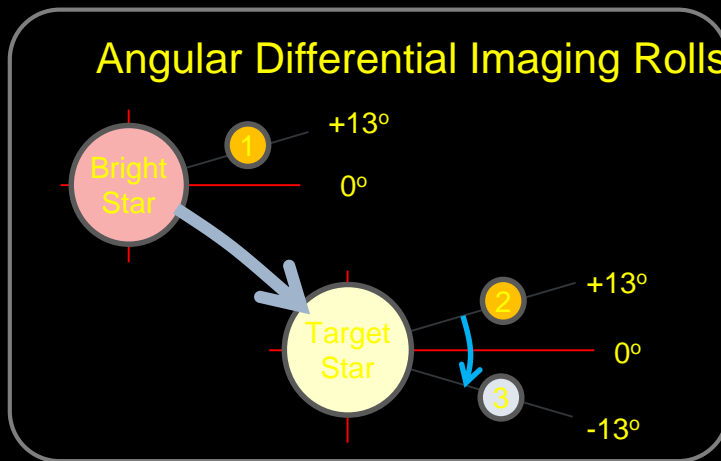
JPL's High Contrast Testbed

Observation: Integration and Chop Cycle

- Break up long observations (e.g. spectroscopy) by “chopping” between reference and target stars (RDI) and different telescope rolls (ADI) to relax observatory and CGI stability requirements
- ~20% of observing time on reference, ~10% on slew / roll overheads
- Bright reference star for each target w/ similar solar angle for thermal stability



Angular Differential Imaging Rolls



WFIRST

CGI TOP LEVEL ERROR BUDGET

575 nm 10% BW

IMG NFOV - Band 1

Revision Date 4/19/2018

L1 Telescope Diameter [m]	
Value	2.37

L2 Star Brightness [mag]	
Value	5.0

L2 Filter Band [nm]	
Center	575.0
Width	10%

L2 Resolving Power	
Value	N/A

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

L2 Planet Integr. Time [hrs]	
Value	10
useable	7

Planet Photon Noise [ppb]	
Req.	1.43
CBE	1.13

Zodi Photon Noise [ppb]	
Value	0.31
CBE	0.24

Diff. Imaging Random Noise (RD) [ppb]	
Req.	0.51
CBE	0.33

L2 Exoplanet Background	
-------------------------	--

Photometry Noise [ppb]	
Alloc.	1.92
CBE	1.41

Perf. Reserve Flux Ratio Noise unalloc.	41%
---	-----

Stellar Leakage Shot Noise [ppb]	
Alloc.	0.88
CBE	0.56

L2 Planet-Star Flux Ratio [ppb]	
Req.	50
CBE	17

L3 Flux Ratio Noise [ppb]	
Req.	5.0
CBE	1.7

L2 SNR	
Value	10.0

Margin over CBE	66%
-----------------	-----

Cont Stability w/Post Proc [ppb]	
Alloc.	2.27
CBE	0.98

L4 Cont Stability w/Chop [ppb]	
Alloc.	2.87
CBE	1.30

Post-Processing Gain	
Value	2.0

L1 Requirement in PLRA	
L2 Requirement in MRD	
L3 Requirement in CGI Spec	
L5 Control Loop	
L4/5 CGI Requirement	

Viewed Scenario	4/19/2018
Disturbance case	IMG NFOV - Band 1
Sensitivity Case	rgt10hr180109
detector	HLC150818_61_10per
Annular Zone (λ/D)	EM PC REQ
MUF	4-5
months at L2	Standard
	63

planet	Fid REQ Band1
Flux Ratio	50.0 ppb
Sep.	225 mas
Host V	5 mag

throughput

core throughput

L4 Coronagraph Mask Effective Throughput	
Alloc.	3.5%
CBE	3.7%

L4 Coronagraph Optics Throughput	
Alloc.	42.2%
CBE	51.5%

L4 Detected Quantum Efficiency	
Alloc.	51%
CBE	57%

L4 Detector Pixels per signal region	
Alloc.	5

L4 Detector Pixels per signal region	
Alloc.	5

L4 Detector Pixels per signal region	
Alloc.	5

L4 Detector Pixels per signal region	
Alloc.	5

L4 Detector Pixels per signal region	
Alloc.	5

L4 Detector Pixels per signal region	
Alloc.	5

measurement noise

static contrast

contrast stability

telescope interfaces

L3 Telescope Throughput	
Req.	82%
CBE	88%

L3 Telescope Throughput	
Req.	82%
CBE	88%

L5 Dark Current [e/pix/s]	
Alloc.	6.1E-04
CBE	5.6E-04

L5 CIC Noise [e/pix/fr]	
Alloc.	2.6E-02
CBE	2.3E-02

L5 Read Noise [e/pix/fr]	
Alloc.	0E+00
CBE	0E+00

Initial Static Incoh. Raw Contrast [ppb]	
Alloc.	5.0
CBE	3.8

Ghost Reflections & Stray Light [ppb]	
Alloc.	0.2
CBE	0.2

Telescope Polariz WFE [nm]	
Value	1.9

L4 Initial Static Raw Contrast [ppb]	
Alloc.	7.00
CBE	5.24

Initial Coherent Raw Contrast [ppb]	
Alloc.	2.0
CBE	1.5

Raw Contrast w/o control [ppb]	
Alloc.	N/A
CBE	1000

Design Contrast [ppb]	
Alloc.	1.8
CBE	1.4

L3 Telescope Wavefront Error [nm]	
Alloc.	77
CBE	71

Coronagraph Fab. & Align Errors [nm]	
Alloc.	105.0
CBE	95.0

Average Raw Contrast [ppb]	
Alloc.	12.1
CBE	8.15

Differential LoS residual [ppb]	
Alloc.	1.57
CBE	0.27

L5 LoS Jitter Sensitivity [ppb/mas]	
-------------------------------------	--

Differential LoS Residual [mas]	
Alloc.	0.50
CBE	0.21

L5 Pointing Control using LOWFS + FSM	
---------------------------------------	--

L3 Observ. Filtered LoS Drift + Jitter [mas]	
Alloc.	0.57
CBE	0.42

Differential Z4-11 WFE Residual [ppb]	
Alloc.	0.73
CBE	0.03

L5 Z4-11 WFE Drift Sensitivity [ppb/pm]	
---	--

Differential Z4-11 WFE Residual [pm]	
Alloc.	70.0
CBE	2.9

L3 Observ. Z4-11 WFE Rate of Change [nm]	
Alloc.	0.07
CBE	0.02

Differential Z12+ Residual [ppb]	
Alloc.	1.02
CBE	0.05

L5 Z4-11 DM Gain Error Sensitivity [ppb/pm]	
---	--

Differential LOWFS + DM Gain Error [pm]	
Alloc.	250
CBE	0.2

L3 Observ. Z4/ Z5-11 WFE Drift [nm]	
Alloc.	2.00/0.25
CBE	0.45/0.05

Diff. Unsuppressed Drift/Jitter [ppb]	
Alloc.	1.10
CBE	0.65

L5 Obs Residual Drift Sensitivity [ppb/nm]	
--	--

CGI internal (DM) Drift [mK]	
Alloc.	1.0E+01
CBE	8.0E+00

L3 OTA-CGI Interface Pupil Shear Drift [μm]	
Alloc.	0.40
CBE	0.20

L3 Observatory WFE Jitter Z4-11 [nm]	
Alloc.	0.25
CBE	0.07

Differential CGI Internal Drift [ppb]	
Alloc.	1.74
CBE	1.09

L5 DM Drift Sensitivity [ppb/mK]	
----------------------------------	--

CGI internal (DM) Drift [mK]	
Alloc.	1.0E+01
CBE	8.0E+00

L3 Observatory WFE Jitter Z4-11 [nm]	
Alloc.	0.25
CBE	0.07

CGI Spec # 681

CGI Spec # 674

CGI Spec # 688

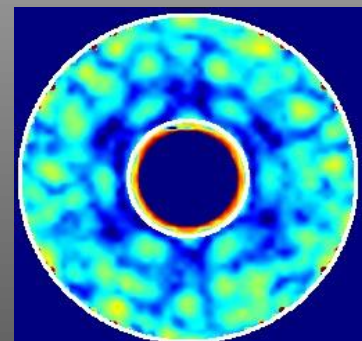
CGI Spec # 680

CGI Spec # 679

CGI Spec # 673

CGI Spec # 689

- Instrument contrast (starlight suppression)** defined in 3 annular rings, for different angular separations from the star
 - Required contrast levels have been demonstrated in the testbed with WFIRST Phase A pupil, HLC in particular has far outperformed required contrast

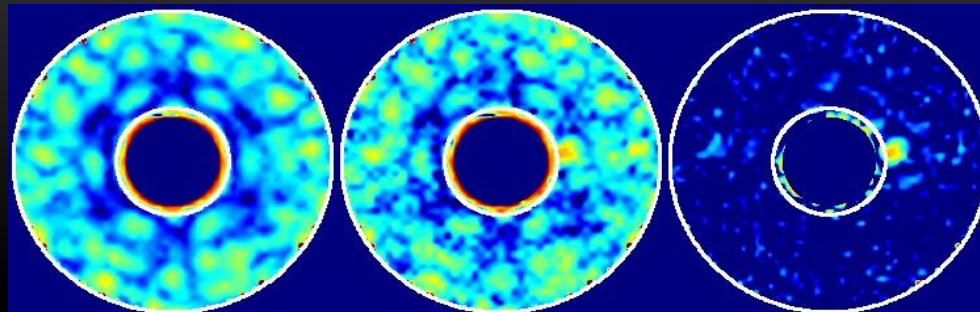


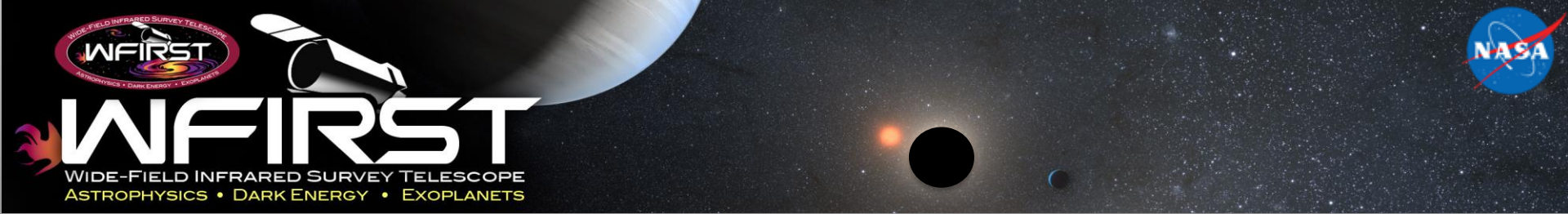
Mode	Current Best Estimate (CBE)	CBE Basis
Imaging with Narrow FoV Raw Contrast	3.8×10^{-9} , 3–4 λ/D 2.5×10^{-9} , 4–8 λ/D 3.8×10^{-9} , 8–9 λ/D	Raw Contrast Error Budget, Validated Against Testbed
Spectroscopy Raw Contrast	1.2×10^{-8} , 3–4 λ/D 8.2×10^{-9} , 4–8 λ/D 1.2×10^{-8} , 8–9 λ/D	Raw Contrast Error Budget, Validated Against Testbed
Imaging with Wide FoV Raw Contrast	3.8×10^{-9} , 6.5–7.5 λ/D 2.5×10^{-9} , 7.5–19 λ/D 3.8×10^{-9} , 19–20 λ/D	Raw Contrast Error Budget, Validated Against Testbed

CGI Predicted Performance: Contrast Stability

- Instrument contrast (speckle) stability** enables subtraction of residual starlight to see the planet.

Requirement	Current Best Estimate	CBE Basis
Imaging with Narrow FoV Contrast Stability	3.5×10^{-9} , 3–4 λ/D 2.4×10^{-9} , 4–8 λ/D 3.5×10^{-9} , 8–9 λ/D	CGI performance budget
Spectroscopy Contrast Stability	1.2×10^{-9} , 3–4 λ/D 0.8×10^{-9} , 4–8 λ/D 1.2×10^{-9} , 8–9 λ/D	CGI performance budget
Imaging with Wide FoV Contrast Stability	0.6×10^{-9} , 6.5–7.5 λ/D 0.4×10^{-9} , 7.5–19 λ/D 0.8×10^{-9} , 19–20 λ/D	CGI performance budget





Thank you for your attention